APL - North Pacific Acoustic Laboratory

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LONG-TERM GOALS

The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) program at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of low-frequency, long-range, deep water, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of NPAL is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on long-range ocean acoustic signal transmissions.

OBJECTIVES

The scientific objectives of the North Pacific Acoustic Laboratory are:

1. To study the spatial and temporal coherence of long-range, low-frequency resolved rays and modes and the dependence upon ocean processes, transmission distance, and signal frequency.
2. To explore the range and frequency dependence of the higher order statistics of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments.
3. To define the characteristics and trends, and determine the relative causes of low-frequency ambient noise on ocean basin scales.

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4. To elucidate the roles of internal waves, ocean spice, internal tides, fronts and eddies in causing fluctuations in acoustic receptions.
5. To improve basin-scale ocean sound-speed predictions via assimilation of acoustic travel-time and other data into numerical ocean-dynamic models.
6. To fully analyze our experiment in the Philippine Sea, the results of which will support all of the objectives listed above.

APPROACH

APL-UW employs a combination of experimental measurements, data analysis, simulations, and theoretical development to address the objectives outlined above. These activities are funneled through two primary avenues. The North Pacific Ambient Noise Laboratory, operated and maintained by APL-UW, provides a full-time laboratory for real-time acoustic measurements at a selection of basin-scale locations, the capability to test various transmission signals, and ambient noise (including marine mammals) measurements in the NE Pacific Ocean. The Laboratory consists of the legacy SOSUS hydrophone receiver network in the Pacific Ocean, and a data processing and archive center at the Applied Physics Laboratory. Figure 1 illustrates the locations of acoustic hydrophone arrays in the Laboratory and major shipping lanes.

The second avenue includes highly focused, comparatively short-term experiments.
We have recently completed an experiment in the Philippine Sea called PhilSea10 [1]. See Figure 2. The principal elements of the APL-UW effort during the 2010 experiment were: 1) a 55-hour continuous transmission from ship stop SS500 at 500 km from the DVLA and a depth of 1000 m, 2) a tow of a CTD Chain along the path toward the DVLA from SS500, 3) a source tow at a depth of 150 m at ranges between 25 and 43 km from the DVLA through the region of a Reliable Acoustic Path (RAP) from the near-surface region to the water column bottom, 4) a series of CTD casts every 10 km from the DVLA back to SS500, and 5) a 55-hour continuous transmission from SS500 at a depth of 1000 m to the DVLA. The primary institutions participating in PhilSea10 were APL-UW, the Scripps Institution of Oceanography (SIO), and the Massachusetts Institute of Technology (MIT). Analysis of environmental data from PhilSea10 is underway, and we recently received the acoustic data from the Distributed Vertical Line Array (DVLA).

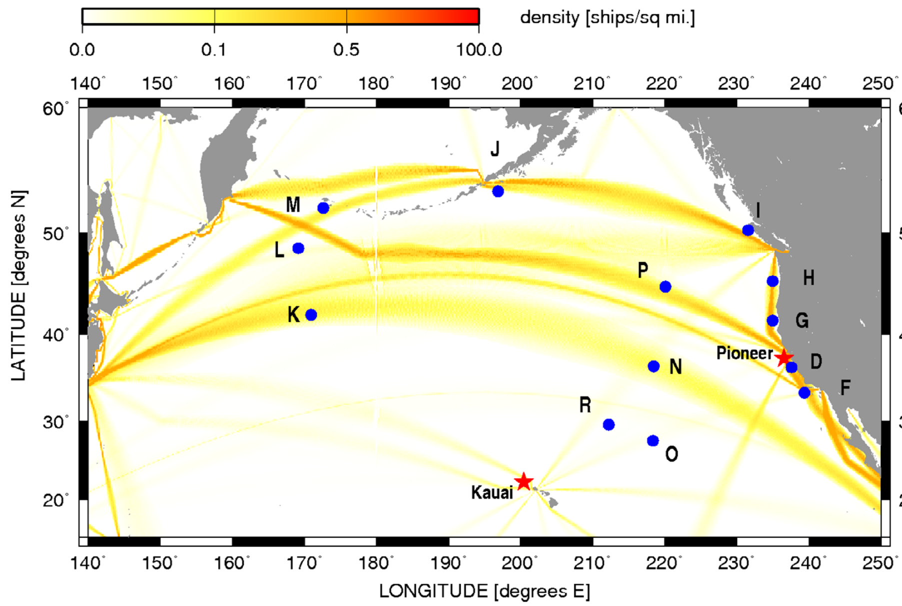

Figure 1. "The North Pacific Ambient Noise Laboratory". The blue circles are receivers: locations D, F and R are exact. All other receiver locations are notional. The red stars indicate transmitters installed under the ATOC program. The color mapping utilizes the "merchant" shipping density from the HITS 4.0 shipping density data base [2]. Note the nonlinear density color scaling.

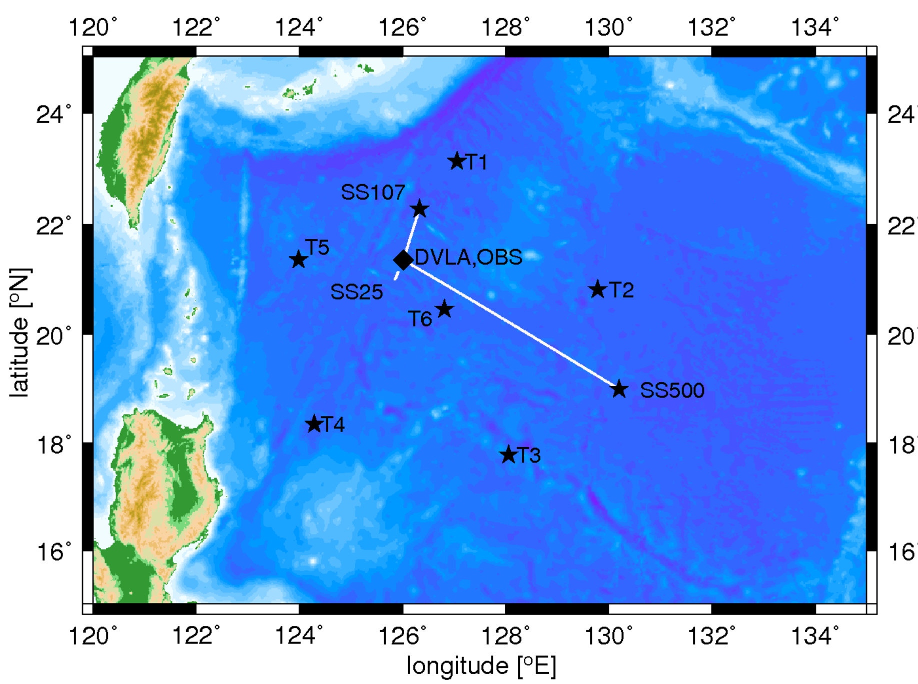

Figure 2. Major elements of PhilSea10

WORK COMPLETED

North Pacific Ambient Noise Laboratory-

Our recent *JASA* paper [3] reports a significant decrease in ambient noise levels at two northern sites where we have been measuring ambient noise levels for more than a decade. A figure from this paper is presented here as Figure 3.

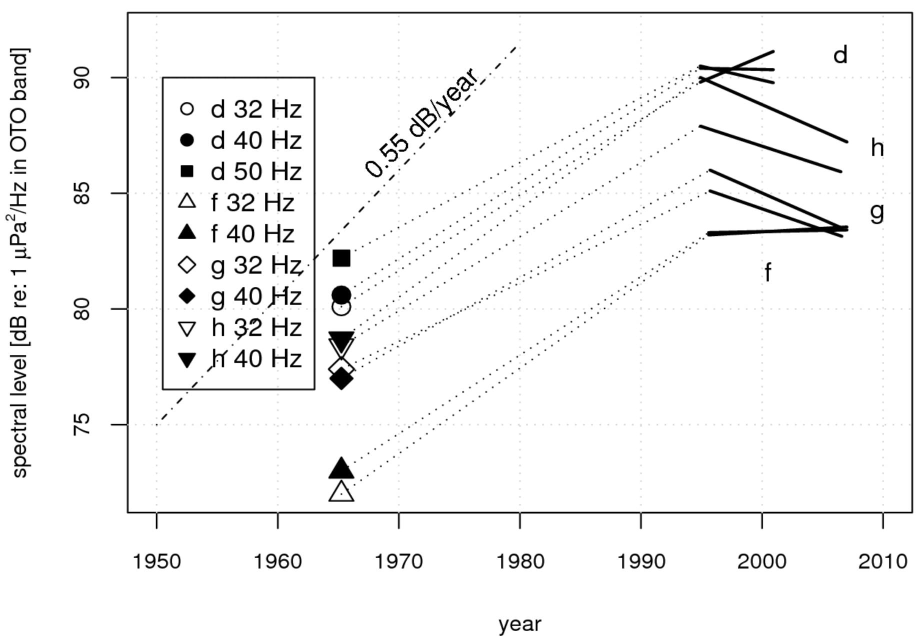

Figure 3. Long-term trends in ambient noise

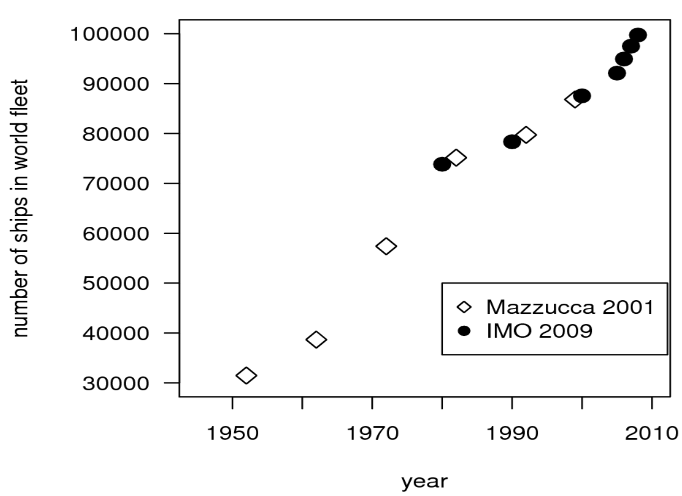

Figure 4. Number of ships in the world fleet.

Ten years ago, we were working with Lori Mazzucca, a graduate student in the University of Washington School of Marine Affairs, and she published [4] some statistics on the size of the world's merchant shipping fleet. Her statistics were deduced from databases such as Lloyd's of London. Her results are shown in Figure 4. Up through 1982, the values she reported came from a book [5]: The values from 1992 and 1998 came from a personal communication [6] with an investigator who apparently had access to Lloyd's or a similar database and reduced the data to these statistics. Of course, the period 1995 and later encompasses our APL-UW time series so it remained of interest to update Mazzucca's figure.

This year, we located additional reduced statistics published on the Internet by the International Maritime Organization (IMO) [7]. They provide values for 1980, 1990 and 2000, and then 2005-2008. These are also plotted in Figure 4. The IMO numbers for 1980, 1990 and 2000 correspond very well with those from Mazzucca (which involved two sources.) This gives us confidence that these IMO values were derived from similar original data sources in similar ways. It follows that the IMO numbers for 2005 to 2008 provide a quantifiable indication of the world merchant shipping fleet over the rest of the period of the APL-UW dataset.

On another subject, M. Ainslie of The Netherlands Organization has questioned whether the levels we reported in [3] represent the average ambient noise level. He presented a theoretical calculation [8] that indicated that the increase in worldwide noise levels is explained by the increase in the number of ships, notwithstanding our recent result. In further discussions, Ainslie explained that his calculation produces an “average noise power” $\langle|p|^2\rangle$, whereas we report a median level.

These two quantities are not the same. As we explained in [9], the median measure is insensitive to sporadic extra-loud events in the noise record. This was desirable because we were comparing statistics from our data set with those generated by Wenz for the 1960s; and Wenz used a semi-manual editing procedure to eliminate time data segments containing extra-loud events. It was Wenz's rationale that the extra-loud events were due to individual ships passing close by the receiver, and he was interested in characterizing the “distant shipping”, i.e., a measure not biased by these sporadic extra-loud events.

Our hypothesis is that the noise level (on, say, daily timescales) due to distant shipping fluctuates moment-by-moment by only a minor amount about a time-averaged “mean” level. We call this process the “background”. A population of short-time background noise measures should be well-described by a Gaussian distribution, and, when this is true, the median will be the same as the mean. Sporadic loud events cause a heavy upper tail in the distribution; the mean of such a dataset would be higher than the median level.

Philippine Sea-

Spatial statistics of internal waves and ocean "spice" (density-compensated sound-speed fluctuations) are important for modeling their effects on ocean acoustic propagation. Previous work has investigated the vertical distribution of spice in experiments, but not the horizontal, and the aspect ratio of these phenomena are crucial for the acoustic modeling. Intermittency and the fact that the spice features are of the same scale size as collocated internal waves complicate the picture. Empirical investigation of these phenomena are key to improved modeling.

An 800 m version of the "towed CTD chain" (TCTD) instrument [10] was used in the Philippine Sea 2010 experiment to attempt to measure temperatures and conductivities in a 2D ocean slice along towpaths of order 100km (see Figure 5). These were to be densely sampled measurements in space and time, from which horizontal strain spectra could be computed along long horizontal paths interpolated amidst the dense samples, at each of many depths. Thus the depth-dependent nature of the horizontal spice statistics could be analyzed in that experiment. Unfortunately the instrument performed poorly, producing only a small subset of useable data in the tows, but we do have some data to work with and we have been proceeding with a modified version of the planned analysis by supplementing the limited TCTD data with the sequence of CTD casts taken nearby in space and time to the analyzed TCTD tow (Figure 6).

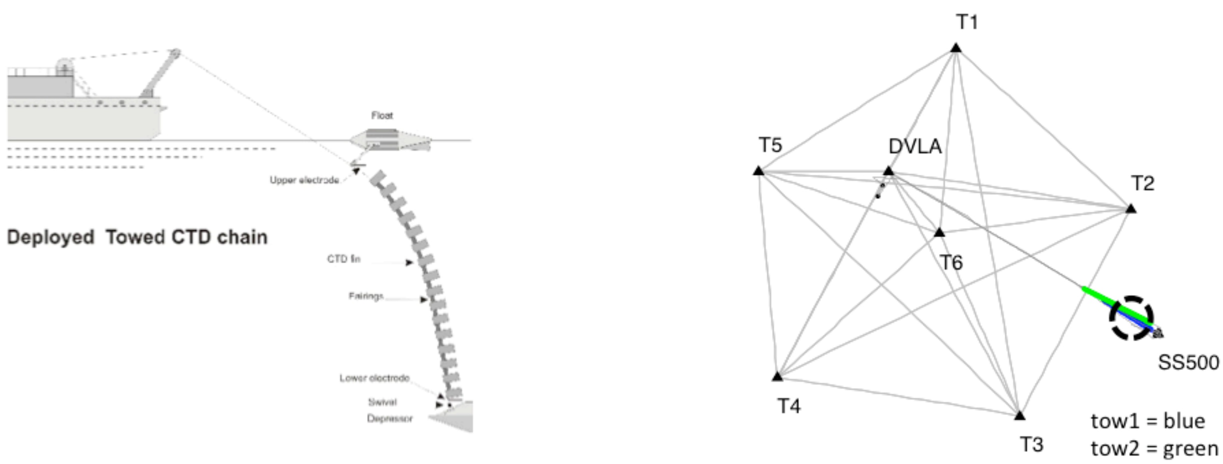

Figure 5. Left: experiment configuration; a 800 m sea cable with 88 CTD sensors is towed behind the ship, with the help of a float and a depressor. Right: experiment geometry; the two TCTD tows were within the 100 km west of ship stop SS500. Tow #2 had better data quality and has been the focus of the analysis.

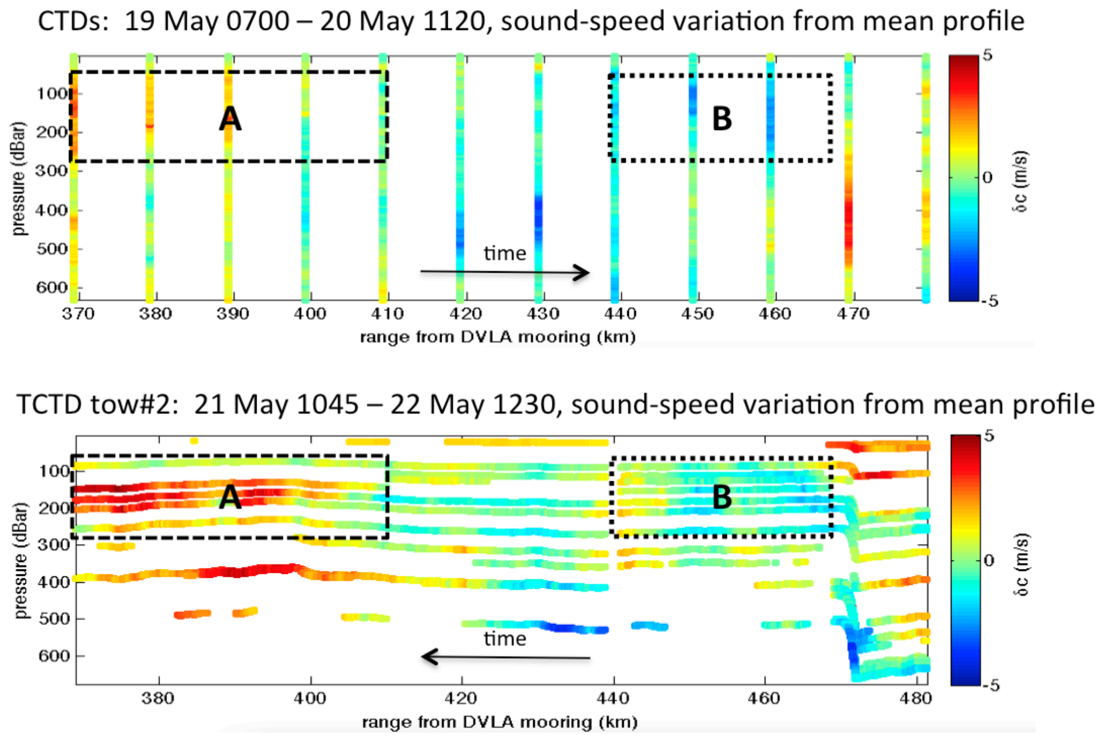

Figure 6. Top: soundspeed anomalies in CTD casts along the TCTD tow track. Bottom: soundspeed anomalies in TCTD tow#2. The mean profile subtracted in both plots is that of the 12 CTD profiles shown.

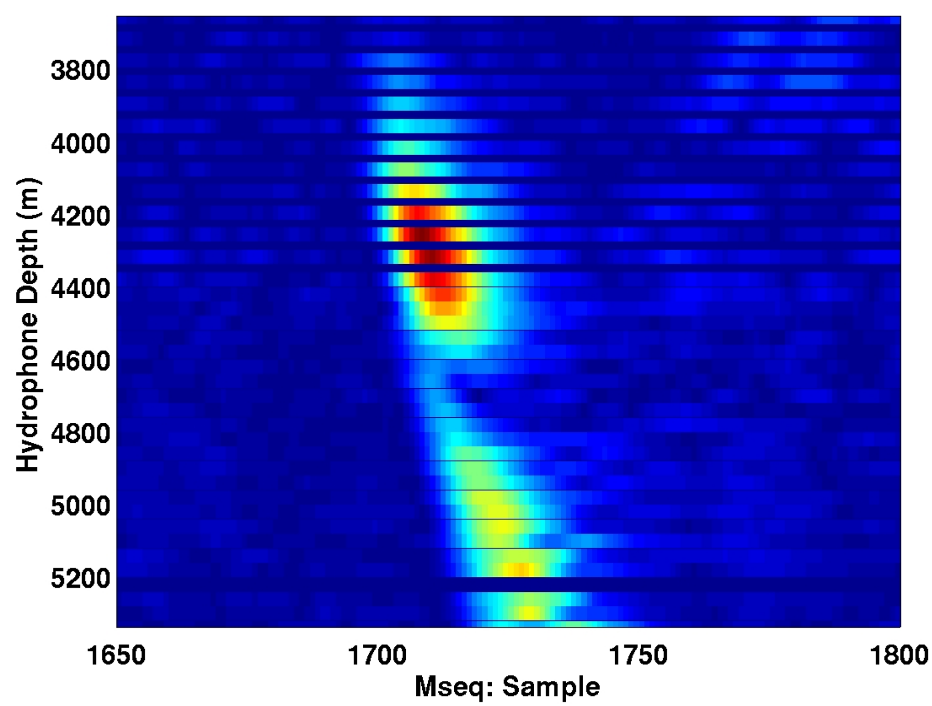

Figure 7. DVLA reception from the 150 depth source drift at 25 km range.

The first DVLA acoustic data to be analyzed from PhilSea10 are from the shallow acoustic source "tow." Figure 7 shows the reception of a single M-sequence on the deep hydrophones of the DVLA. The HX554 source was suspended to a depth of 150 m and continuously transmitted a M-sequence with a carrier frequency of 57 Hz while the ship moved from 25 to 43 km away from the DVLA. The white line labeled SS25 in Figure 2 shows the approximate line of the drift. The "tow" was actually a controlled drift since the ship was moving with the current away from the DVLA and only the bow thruster was used to maintain orientation and the drift path. This was done to limit the ship's radiated noise. The purpose of the exercise was to study the reliable acoustic path (RAP) range and the effect of the bottom on the RAP range. The RAP range was predicted to be approximately 30 km.

We have been using the Navy Standard Parabolic Equation, NSPE 5.4, for the 107 km simulations of PhiSea2009 configurations (SS107 on Figure 2). These Monte Carlo simulations require wall-clock timescales of months. Corresponding 500 km calculations for the PhilSea2010 configuration (SS500 on Figure 2) do not appear feasible with this code on our cluster. We have therefore been investigating an upgrade to our computational capacity.

The simplest option would be to migrate NSPE to a new target cluster, except that NSPE has distribution restrictions that preclude this.

The next option was to migrate the pertinent parts of NSPE to a code base that could be targeted for a new cluster. NSPE implements two parabolic equations: RAM and the SS-Fourier PE. RAM is widely used in our long-range community, so we investigated migrating RAM.

The original Michael Collins RAM is available as open source, i.e., from OALIB. Matt Dzieciuch has ported that code to Matlab, and Brian Dushaw has ported Matt's code back to Fortran. Collins' RAM consists of several features: (1) the “split-step Padé” algorithm, (2) computational tricks to increase speed, and (3) specialized I/O routines. The split-step Padé algorithm is the heart of the code. The computational tricks presume that the sound speed field, the seafloor depth, and/or the bottom composition remain unchanged for many range grid points. This is a good model for many deterministic calculations, but not relevant for what we need. The input sound-speed field for a scattering calculation contains a different sound-speed field at each range step. Most of RAM's computational tricks can therefore be eliminated for our application. This also eliminates the applicability of all specialized I/O routines.

In addition, RAM is a single frequency calculation, whereas our simulations require a time domain result. This suggests that we needed a “broadband” application with embedded split-step Padé engines at each of many frequencies, with a back-end inverse Fourier transform.

We have therefore developed a “modified RAM” suitable for deployment without restrictions to any compute cluster. This code uses Collins' split-step Padé formulation, but eliminates many of the tricks used in recalculating the implicit finite-difference matrices, and also substitutes a simple and straightforward tri-diagonal solver. Those tricks made RAM fast for a certain class of problems, but most of that gain is not applicable to our scattering problems.

Graduate student Andrew White passed his General Exam in June this year. Most of the year has been dedicated to modeling acoustic propagation of signals transmitted by APL-UW during the pilot study/engineering test PhilSea09.

White's modeling of the environmental variability during PhilSea09 consists of two separate simulations. In the first simulation, approximately 200 independent, Garrett-Munk (GM) internal wave perturbed random oceans were generated, and then the acoustic field from a point-source was propagated through each of these oceans. The purpose of this simulation was to create an ensemble from which to calculate statistics such as the scintillation index (SI) for each of the four arrival groups corresponding to the ray paths shown in Figure 8. This method is commonly referred to as the Monte Carlo Parabolic Equation method in the deep-water acoustics community.

For the second simulation, the internal wave field in one model ocean is evolved in geo-time. The GM spectrum is bounded in temporal frequency by the inertial (32-hour period at this latitude) and buoyancy (10-20 min. period) frequencies. A GM internal wave perturbed ocean is evolved over 10 inertial periods, or about 320 hours, at a time-step of 240 sec. At each time-step the acoustic field from a point-source is propagated to a range of 107 km.

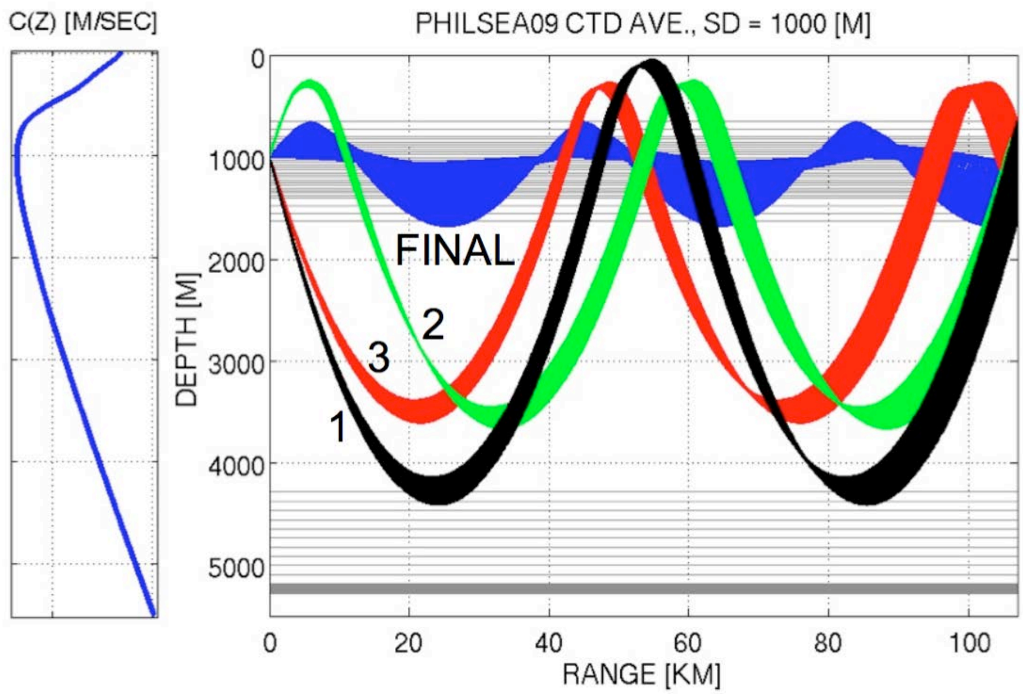

Figure 8: Ray paths of acoustic waves that reach the upper hydrophones at 107 km range.

In Figure 8, ray paths refract according to the sound-speed profile shown at the left of the Figure. Only purely refracted rays which reach the receiving array at 107 km range are plotted. Hydrophone depths are represented by gray lines. Note that the spacing in depth between hydrophones was variable. The gray band near 5 km depth is a group of closely-spaced hydrophones. In this work, receptions on the lower section of hydrophones were not considered. Paths are numbered in the order of their arrival time at the depth span of 1500-1600 m at the receiver for a pulsed source.

NEW RESULTS

North Pacific Ambient Noise Laboratory-

Figure 4 clearly quantified the belief that the number of ships has continued to increase with time. But the trends we see in our acoustical records suggest that the shipping traffic contribution to oceanic ambient noise is decreasing. At first thought, one might think the world fleet size to be a reasonable indicator for oceanic ambient noise, so this new result seems counter-intuitive. More research is required to understand and/or resolve this apparent contradiction.

As mentioned earlier, our oceanic ambient noise statistics are based on medial levels, not the average noise power. These two quantities are not the same. Our hypothesis is that the noise level (on, say, daily timescales) due to distant shipping fluctuates moment-by-moment by only a minor amount about a time-averaged “mean” level. We call this process the “background”. A population of short-time background noise measures should be well-described by a Gaussian distribution, and, when this is true, the median will be the same as the mean. Sporadic loud events cause a heavy upper tail in the distribution; the mean of such a dataset would be higher than the median.

This difference has now been proven with our North Pacific ambient noise datasets. The narrowband noise level distributions for sites D, F and G (see Figure 1) have been shown [3] to have heavy upper tails. We therefore computed the population mean for each one-third octave band across the entire dataset (6 to 12 years of data) for sites D, F and G, and compared them to the population medians. The results for all three sites confirm that the mean measure is 3 to 4 dB higher than the median. This new consistent result suggests that Ainslie's average noise power is related to our distant shipping measure by some transformation that incorporates the frequency and strength of loud events. We are developing a theory to define this transformation.

This issue is of considerable interest to the ASW community, which has long sought a characterization of the frequency and duration of “quiet periods” (which could be considered the complement of loud events), and the ocean acoustic ecology community, which is currently striving to characterize, measure and predict noise exposure in the marine environment.

Philippine Sea-

Ambient noise levels measured during the 2010-2011 Philippine Sea experiment on the Scripps DVLA and reported in [11] show an “unexpected" decrease in level as depth decreased from about 1000m to the surface.

To infer whether or not this kind of ambient noise profile is to be expected, we performed a simulation using the Navy standard “Dynamic Ambient Noise Model” (DANM) in non-dynamic mode. These calculations do not include any scattering mechanisms, and utilize purely “deterministic” monochromatic transmission losses from sea surface sources (ships and wind waves) to selected receiver depths.

The code was executed at the APL-UW NPAL secure processing facility (because the bathymetry database DBDB-V is a classified database.)

Ambient noise levels for depths 50m, 100m, 150m, …....1000 m are shown in Figure 9 for three frequencies: 25Hz, 100Hz and 300Hz. The levels are decibel equivalents for density values, i.e., measured in a 1 Hz band. Further interpretation remains questionable: we believe these predictions are indicative of the contribution from "distant shipping" because the areal integration extends out to a radius of approximately 1000 nm. The calculation does not include any contributions from discrete ships --- which would represent "local shipping"---but the areal integration appears to start at a radius of 0 nm, i.e., overhead. Additionally, it is unclear to what extent the wind-generated surface noise is incorporated into this calculation.

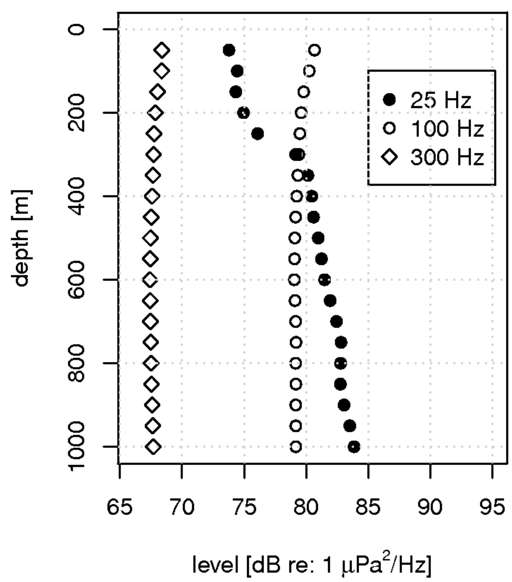

Figure 9. DANM predictions for the vertical noise profile, Philippine Sea experiment.

The profile at 25Hz is likely dominated in the model by distant shipping. (There are no biological contributions in DANM.) This profile does have a decrease of about 10 dB from the deep sound channel axis (approximately 1000 m) to 50 m. We are not sure what sources influence the predictions at 100Hz and 300Hz, but the model suggests these levels are nearly constant across the depths simulated. These results were distributed to collaborators in our community in Reference [12].

The TCTD pressure, temperature, and salinity measurements are used to compute the density-based and sound-speed-based components of vertical displacement, each via the same equation of state [13], according to the methods of Henyey et al. [14]. Other APL work has already focused on studying the vertical variation of spice in the Philippine Sea by similar methods [15]. By definition, these density and sound-speed components of displacement diverge in regions of ocean spice. The analysis here focuses on wave number spectra of horizontal strain, the horizontal derivative of the displacement. The density-based strain spectra are due entirely to internal waves, while the sound-speed-based strain spectra are due to both internal wave and spice components. We expect the sound-speed-based spectra to generally be larger than the density-based ones, the imaginary part of their cross spectra to be zero, and the real part of their cross spectra to be close to the density-based spectra. We can use these

theoretically-expected features to check that the data-based results were computed correctly. The difference between the sound-speed-based and density-based spectra then corresponds to the amount of spice present.

In Figure 10 we see regions of spice in the lower part of dataset for box A (see Figure 6) and the middle of dataset box B. All the results for dataset box B, and the results for the lower part of dataset box A, agree with the expected theoretical checks described above. However, the results for the upper part of dataset box A do not – the imaginary part of the cross-spectrum are close to zero, but the density-based strain spectrum is larger than the sound-speed-based one, and the real part of the cross-spectrum follows the sound-speed-based spectrum rather than the density-based one (e.g. at 140m in dataset A, also seen in other results not shown for dataset box A). This is contrary to the theory. Yet the code is successful in computing results which pass these theoretical checks in all the vertical CTD cases, and a number of other horizontal TCTD cases. And when the same analysis is instead run on simulated data generated from a Garrett-Munk internal wave displacement spectrum [16], the density-based and sound-speed-based spectra are identical because there is no explicitly separate spice in that simulated data. This all suggests that this discrepancy between measured results and theory may concern how we handle features in the data as opposed to troubles in the code itself:

The displacement quantities from which the strains are computed are based on the non-adiabatic components of the density and sound speed and their vertical derivatives. The towed chain data has problems with vertical gaps, so not only must we vertically interpolate TCTD sensor data, we also use smoothed averages of our conventional CTD casts as a background field to provide the adiabatic density and sound speed components and the vertical derivatives. Presently our calculations use range-independent smoothed averages of the CTD casts for this background field, but it may be necessary to use a range-dependent smooth background instead. Also we note the timing of the CTD and TCTD data collection – the ship acquired CTD casts in the direction of increasing range from the DVLA, then turned around and took the TCTD data in the opposite direction, so the right sides of the two plots in Figure 6 are closest together in time. This means that the background field for dataset B was computed from data that was closer in time to its corresponding TCTD data than was the case for dataset A. We are presently exploring these possibilities in hopes of explaining this discrepancy between measurement results and theory in dataset A.

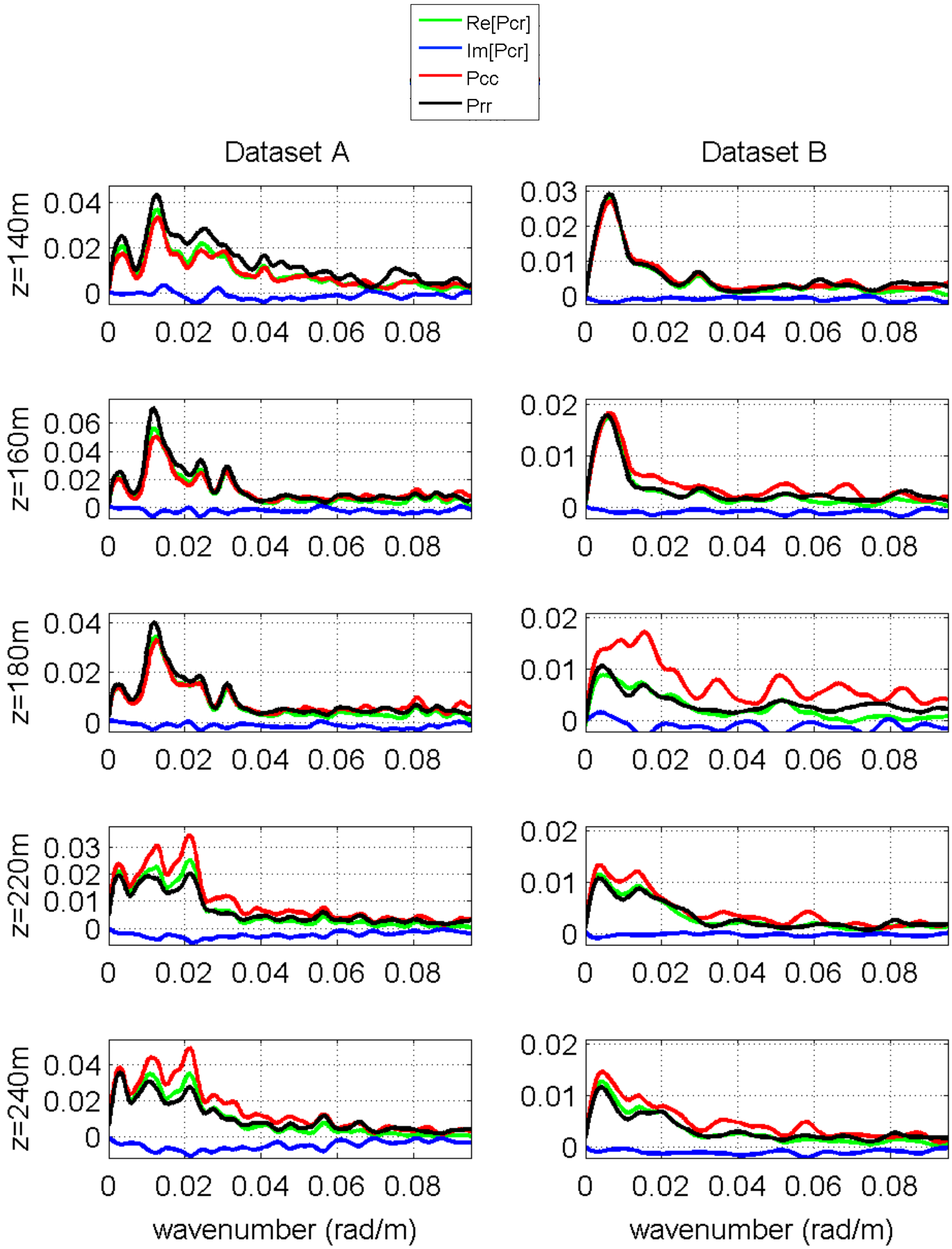

Figure 10. Spatial spectra of horizontal gradients in displacement (i.e. horizontal strain), at depths 140-240m, along the sub-segment of TCTD tow #2 shown in Fig. 2. The same depths were used for both datasets A and B. Prr is the power spectral density of the density-based strain, Pcc is that of the sound-speed-based strain; the other two lines are the real and imaginary parts of their cross-spectral density Pcr.

The end interest in these investigations is toward improvement in acoustic propagation modeling and understanding, ultimately looking to questions like, "Is it beneficial to bring a TCTD along in long-range ocean acoustic experiments in the future? Must one aim to obtain a fully-sampled (in time and space) dataset for direct use in propagation modeling, or could a spectral description suffice?" Unlike for linear internal waves, a spectral description of the distribution of spice is not a full description of its distribution – spice is a greatly intermittent and non-Gaussian process, with "blobs" here and there. In focusing this work on spectral descriptions of spice, we acknowledge that it is an initial step toward the understanding of this phenomenon, but not a complete enough description to fully model spice distributions directly from the spectra. The benefits will depend on application – tomographers typically focus on travel-time variations, which are chiefly affected by low-wavenumber variability in the sound-speed field. But phenomena like scattering and deep-fades manifest themselves more in intensity variations, which are chiefly due to higher-wavenumber variations in the sound-speed field. If successful, the spectral results in this work would provide an empirical view into the horizontal scales of variability of both internal waves and spice in the ocean.

As mentioned in the Work Completed section, in the second simulation, the internal wave field in one model ocean is evolved in geo-time. The GM spectrum is bounded in temporal frequency by the inertial (32-hour period at this latitude) and buoyancy (10-20 min. period) frequencies. A GM internal wave perturbed ocean is evolved over about 10 inertial periods, or 320 hours, at a time-step of 240 sec. At each time-step the acoustic field from a point-source is propagated to a range of 107 km for eventual comparison with the actual data collected during PhilSea09.

A simulated time series (see Figure 11) for acoustic intensity is formed in this manner and correlation functions and spectra will be computed from this time series for each of the four arrivals. The purpose of this simulation is to form predictions for time-dependent statistics. Figure 12 presents the actual time series of APL-UW signal receptions recorded on Scripps' hydrophone array during PhilSea09. These receptions correspond to the modeled receptions shown in Figure 11. The y-axis is intensity in decibels, with an offset applied for visualization. Notice the long-period variability observed in arrival one which is not modeled by the GM internal wave perturbed simulation. The GM model characterizes a large amount of oceanographic data, and has been seen to generally agree with observations in the deep ocean and at geographic locations sufficiently removed from strong sources of internal waves. There have been, however, exceptions to this rule. The parabolic equation model contains all of the relevant physics, so if the hypothesis is incorrect, the GM model's (or the values used as its parameters') applicability in this region will fall into question. Though this would be a negative result, that result would be significant –as the Monte Carlo method involving the GM spectrum of internal waves is generally assumed to work when more efficient analytic approaches cannot be applied. Obviously, the next major step is to compute the relevant statistics for a detailed comparison.

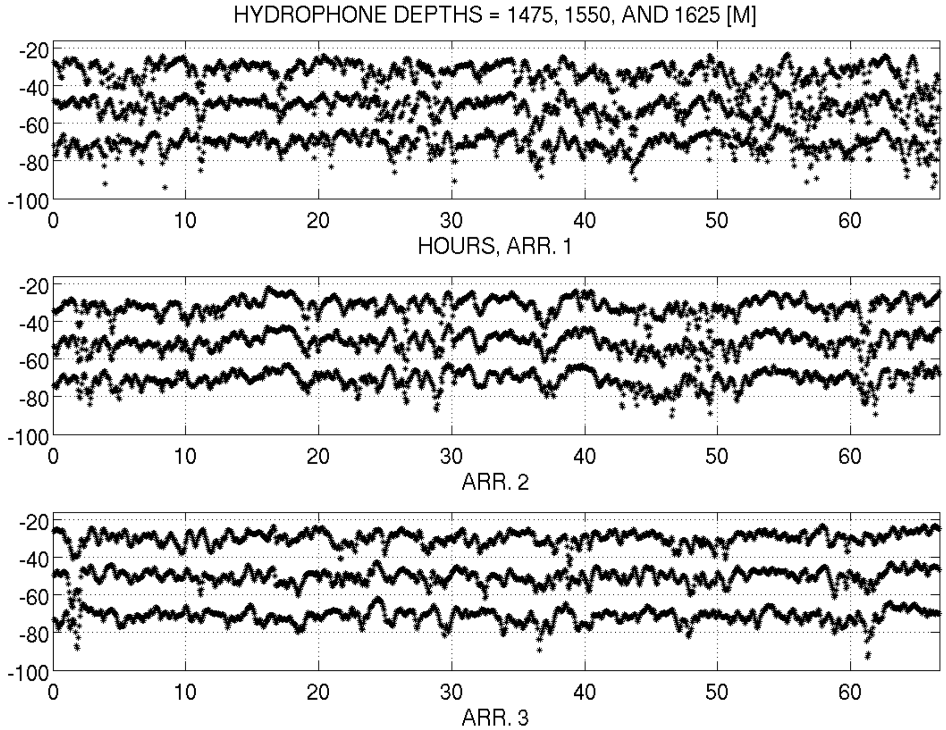

Figure 11. Example time series from the geo-time evolved internal wave ocean simulation. Shown in the top panel are the modeled receptions of ray path arrival one recorded on three adjacent hydrophones, at 1475, 1550, and 1625 meters depth. The y-axis is the relative intensity in decibels, with an offset applied for visualization; source level is not taken into account. Panels two and three show ray path arrivals two and three. All three paths correspond to those depicted in Figure 8.

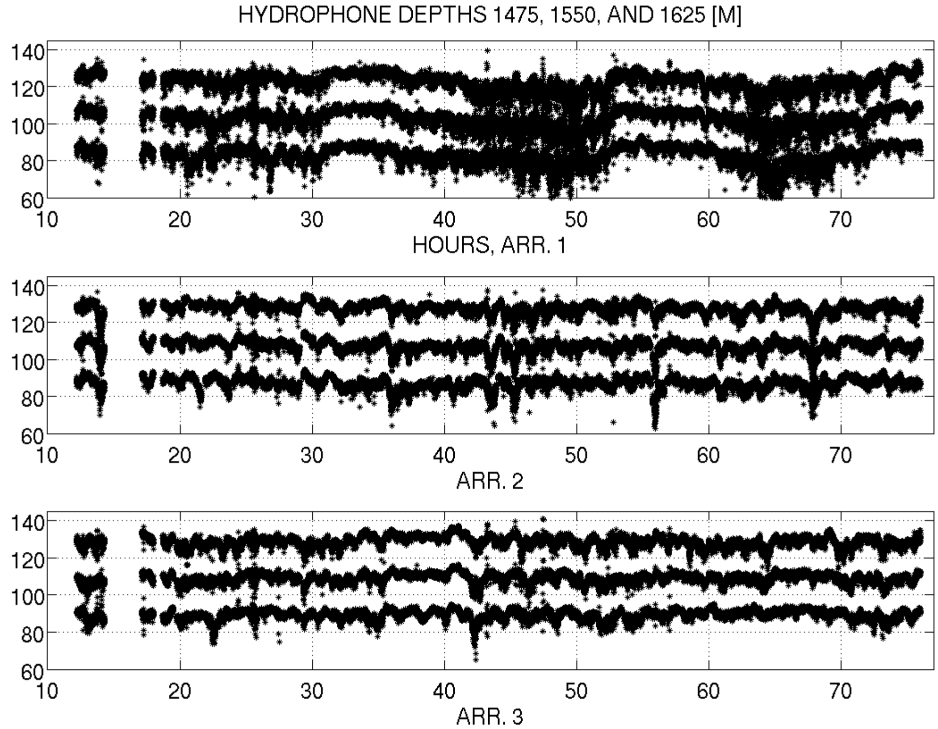

Figure 12. Actual time-series of APL-UW signal receptions recorded on Scripps' hydrophone array during PhilSea09. These receptions correspond to the modeled receptions shown in Figure 11. The y-axis is intensity in decibels, with an offset applied for visualization. Notice the long-period variability observed in arrival one which is not modeled by the GM internal wave perturbed simulation.

RELATED PROJECTS AND COLLABORATIONS

A large number of additional investigators have been involved in ONR-supported research related to the NPAL project and participate in the NPAL Workshops, including Art Baggeroer (MIT), J. Beron-Vera (UMiami), M. Brown (UMiami), J. Colosi (NPS), N. Grigorieva (St. Petersburg State Marine Technical University), F. Henyey (APL-UW), V. Ostashev (NOAA/ETL), R. Stephen (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), Peter Worcester (Scripps), and others. In addition, we have begun close collaboration with Gerald D'Spain who is funded by the signal processing code of ONR.

IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic surveillance, communication, or remote sensing of the ocean interior. The data from the NPAL network, and the special NPAL experiments, indicate that existing systems do not exploit the limits of acoustic coherence at long ranges in the ocean. Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetry, and other data types with ocean general circulation models have the potential to improve our ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of ocean variability.

TRANSITIONS

1) Regarding "Ray 1.49": We sent our upgraded version of this ray-tracing code to Art Newhall at WHOI and Paul Baxley at SPAWARSSC for updating the OALIB website.

2) Regarding "CAFI": We sent our version of Stan Flatté's statistical acoustic code to Mike Porter at HLS Research for inclusion in the OALIB website.

PUBLICATIONS

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